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Ship Materials Engineering Department

Damping Loss Factor Determination of Glass and Graphite Fiber Composites

by

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nonlinearly with frequency. The 90 degree material exhibited a higher damping loss factor than the 0 degree, varying nonlinearly with increasing frequency. In the 90 degree orientation, the glass fiber composite had loss factors that was approximately a factor of 2 greater than the 0 degree orientation. The 0 degree AS4/PEEK had a loss factor that was approximately equal to that of the 0 degree AS4/3501-6. The 90 degree AS4/PEEK had a loss factor that was approximately 50% less than the AS4/3501-6 and 25% greater than the S2-glass/3501-6. (Keywords: vibration damping; structural composites; joints; shipbuilding; (KR) ←

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LIST OF ABBREVIATIONS

Å	angstrom
A-D	analog to digital
APC-2	AS4 graphite/polyetheretherketone composite material
ASTM	American Society for Testing and Materials
DTRC	David Taylor Research Center
FFT	Fast Fourier Transform
ft	feet
ft-lb	foot pound
Hz.	Hertz (cycles per second)
ILS	Interactive Laboratory Software
in.	inch
Msi	million pounds per square inch
PEEK	polyetheretherketone

ABSTRACT

Material damping of laminated composites is experimentally determined using a cantilever beam test with an impulse excitation. Data acquisition and manipulation is carried out using both an IBM PC-AT and a GenRad 2500 Series FFT Analyzer. Unidirectional continuous fiber 0 and 90 degree laminates were fabricated from glass/epoxy (Hercules S2-Glass/3501-6), graphite/epoxy (Hercules AS4/3501-6) and graphite/polyetheretherketone (ICI AS4/PEEK [APC-2]) to investigate the effect of fiber and matrix properties as a function of frequency, up to 1000 Hz., on the damping of composites. The S2-glass/3501-6 composite had a higher loss factor than the AS4/3501-6 in the 0 degree orientation with the loss factor for the AS4/3501-6 exhibiting a linear increase with increasing frequency and the loss factor for the S2-glass varying nonlinearly with frequency. The 90 degree material exhibited a higher damping loss factor than the 0 degree, varying nonlinearly with increasing frequency. In the 90 degree orientation, the glass fiber composite had loss factors that was approximately a factor of 2 greater than the 0 degree orientation. The 0 degree AS4/PEEK had a loss factor that was approximately equal to that of the 0 degree AS4/3501-6. The 90 degree AS4/PEEK had a loss factor that was approximately 50% less than the AS4/3501-6 and 25% greater than the S2-glass/3501-6.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Composite materials are routinely utilized for their high strength and stiffnesses per unit weight. Another characteristic that is often considered is the inherent vibration damping characteristics of this class of materials.

In many structural applications, damping is a primary concern. For most structural applications, the majority of energy dissipation occurs from frictional sources such as bolted, riveted and bonded joints as well as from aero or hydrodynamic damping. In applications where the number of joints are minimized, the material damping becomes increasingly important. Since one of the advantages of composites is the ability to minimize part numbers, and a reduction in energy dissipation normally provided by these joints occurs, a thorough understanding of the role of material damping becomes increasingly important.

There have been numerous experimental investigations to determine the vibration damping loss factor of composite materials.(1-4) These investigations have been motivated by the belief that the material has an inherently high vibration damping loss factor, compared with conventional structural materials, i.e. metals. The rationale used to arrive at this conclusion comes from knowledge of the damping loss factor of the material constituents.

The polymeric materials used as the matrix for organic matrix composites in general have a high vibration damping loss factor. In bulk form, these linear viscoelastic materials have been shown to have loss factors more than an order of magnitude greater than structural metallic materials. When used in the composite form, even though the relative volume fraction of polymeric material is typically only about 40%, the matrix material should provide a

significant contribution to the material damping loss factor.

Material damping can be defined as any material characteristic which allows for the conversion of mechanical energy into some other form of irrecoverable energy. In conventional metallic systems, this energy dissipation occurs through the transformation of mechanical energy into heat. For composite materials, there are numerous sources of energy dissipation such as the viscoelastic response of the material constituents, thermoelastic conversion of mechanical energy into heat, friction at the fiber matrix interface and damage initiation and growth.

Although polymer matrix composites are normally considered to be linearly viscoelastic, most experimental investigations report loss factor for a specific material or laminate configuration without mention of the frequency at which the material was tested. This effort was undertaken to investigate the viscoelastic characteristic of glass and graphite fiber reinforced epoxy matrix and graphite/polyetheretherketone (APC-2) composites. To determine the effect of fiber on the loss factor of composites, the glass and graphite systems investigated used the Hercules Corp. 3501-6 epoxy matrix. To investigate the effect of matrix material, AS4 graphite fiber preimpregnated with 3501-6 epoxy and polyetheretherketone was examined.

The information developed in this investigation will be utilized in an analytical model to predict the damping loss

factor of a general laminated beam using the same material systems. The model that will be utilized requires determination of the complex moduli for the materials. Complex moduli determination is accomplished through proper selection of laminate configuration. The storage modulus can be determined using standard ASTM test configurations, while the loss modulus is obtained from the determination of the loss factor, η, using the relationship that

$$\eta = \frac{E''}{E'} \tag{1}$$

where E'' is the loss modulus and E' is the storage modulus. This information will be then used as input to a general viscoelasticity model for analytical determination of the damping loss factor.

In the investigation on the effect of resin, only a limited data base was developed for the graphite/PEEK. It was felt that the effect of matrix could be best determined by utilizing a material system that had properties that were much different than the epoxy. For example, the PEEK material is a semicrystalline material which at high strains will plastically deform. The APC-2 composite material is available in prepreg form from ICI which allows for reliable, quality fabrication . In addition, this material has been produced for a number of years and is considered by many to be the premiere thermoplastic in regard to its impact performance. Furthermore, S2 Glass/PEEK prepreg is

available so that subsequent testing will enable the determination of the full effect of matrix and fiber on the damping loss factor of composites.

The information presented herein is a compilation of data developed at the David Taylor Research Center (DTRC) and the University of Delaware, Center for Composite Materials.

EXPERIMENTAL SETUP

The experimental apparatus used at DTRC is shown in figure 1. The major components include a clamping block, test specimen, modally tuned instrumented impact hammer, non-contact eddy current probe, and x-z vernier. The test specimen is a flat laminate that is supported horizontally as a cantilever beam in the clamping block. The specimen width in all cases was nominally 1 inch. All specimens were 20 plies with a thickness of approximately 0.10 inches. To ensure that the specimens were uniformly clamped, tool steel rods are inserted into the main support block, with linear bearing inserted into the removable clamping block. The force hammer, model PCB 2496, is a modally tuned impact hammer which has removable tips of various hardness. The non-contact eddy current probe, Kaman model KD2310-3U, is a motion transducer which is positioned near the tip of the specimen.

The signals from the eddy current probe and the instrumented force hammer are read into an IBM PC-AT using a MetraByte DAS16 A-D high speed data acquisition board. A Fast Fourier Transform

(FFT) is performed on the beam tip displacement vs. time information using the Signal Technologies Interactive Laboratory Software version 6.1. The loss factor is determined using the half power band width method. The resonant frequency and the half power points are determined by performing a fourth order curve fit of the transfer function obtained from the ILS software. Details of the procedure are given in reference 5.

Complimentary work was performed at the University of Delaware using similar equipment to that described above. There are, however, several major differences. First, uniform clamping was achieved by incrementally tightening the clamping screws. The base plate is bolted to a unistrut embedded in a large concrete pedestal which provides vibration isolation. Finally, the eddy current probe holder is not attached to the base plate, but instead is free standing. This apparatus is shown in figure 2.

Specimens fabricated at the University of Delaware also had widths of 1 in. but were 8 and 32 ply unidirectional laminates with thicknesses of approximately 0.04 and 0.16 inches, respectively. In place of the modally tuned impact hammer, an electromagnetic hammer was designed and fabricated. This enabled the user to electronically control the impact force level and location of impact. The signals from the force and motion transducer are then input into a GenRad 2500 series FFT Analyzer for determination of the half-power points and the resonant frequency.

SPECIMEN GEOMETRY

To determine the viscoelastic characteristics of the composites, the loss factor as a function of frequency was determined. The motivation for this effort is to experimentally determine the loss modulus of the composite materials, which can be utilized in structural analysis routines. As such, loss factor determination was desired at low frequencies, below 1000 Hz. In addition, it was decided that the loss factor of the first resonant frequency only would be determined.

In order to vary the first resonant frequencies of the composite specimens, it was necessary to change the specimen length. The natural frequency for a clamped-free beam is given by the relationship

$$\omega_n = \left(\frac{k_n t}{L^2} \right) \sqrt{\frac{E}{12\rho}} \tag{2}$$

where ω_n is the frequency of the n^{th} mode, t is the laminate thickness, L is the beam length, E is the bending stiffness, ρ is the density and k_n is the coefficient for the n^{th} frequency.(6)

In order to determine the material's characteristic complex moduli, E^*_1, E^*_2 and G^*_{12}, specimen configurations of 0, 90, and $\pm$ 45 were used for the vibration testing. These configurations will allow for the determination of the material loss moduli using the experimental set-up described above. In this paper, only the results for the 0 and 90 degree orientations will be

discussed. For determination of the storage moduli, the same laminate configuration was utilized but with different thicknesses. Standard test procedures, as given in reference 7, were used for the determination of the storage modulus. The storage modulus information will not be reported herein.

SPECIMEN FABRICATION

The unidirectional composites constructed for this program were made from unidirectional prepreg tape. The materials used were glass/epoxy (Hercules S2-Glass/3501-6), graphite/epoxy (Hercules AS4/3501-6) and graphite/polyetherether-ketone (ICI APC-2). The glass and graphite/epoxy specimens (fiber volume fraction is 65%) were fabricated in-house according to the manufacturers recommended cure cycle. The graphite/PEEK (fiber volume is 61%) specimens were fabricated at the University of Delaware in a compression molding press according to the manufacturers recommended processing cycle that yields a crystalline volume fraction of approximately 30%. Some additional graphite/epoxy(Hercules AS4/3501-6 with 61% fiber volume fraction) specimens were fabricated at the University of Delaware following the manufacturers recommended cure cycle to determine the consistency of the test procedures.

All panels were trimmed and cut to size on a surface grinder with a diamond cutting wheel. Specimens were then ultrasonically inspected to verify that no damage was present due to either processing or machining. A 1 x 1 in. piece of aluminum foil was

then bonded to one end of each specimen. This was necessary to provide a conducting surface which could be monitored by the non-contact eddy current probe.

CLAMPING APPARATUS

The fixturing used to clamp the specimen must be carefully designed to ensure that no extraneous loss mechanisms would occur. These may arise from the creation of damage in the material or through frictional losses at the clamped region. To eliminate damaging the specimen, a ply of TX-1040 peelply was placed between the specimen and fixture, and the specimens were clamped in the fixture to a torque of 10 ft-lb. Ultrasonic inspection of the specimens after testing indicated that no specimen damage occurred.

Another feature of the clamping apparatus is the use of the guide rails. These consisted of tool steel rods mounted into the main clamp block with linear bearings mounted into the movable clamp block. This feature insures that there is no eccentric loading on the clamped specimen.

To isolate the apparatus from the environment, all clamping plates were made of low carbon steel plate with a minimum thickness of 1.0 inch. The entire apparatus was then bolted to a 3 in. thick steel plate with dimensions 3 x 3 ft. This plate is attached to a load frame via isolation springs.

The clamping apparatus used at the University of Delaware

consisted of a cold rolled steel base plate and clamping block which were mounted to a unistrut embedded in a large concrete pedestal, shown in figure 2. Uniform clamping was achieved by incrementally tightening the clamping screws. No guide rods were utilized.

ELECTROMAGNETIC HAMMER

At DTRC, the specimens were excited using a modally tuned impact hammer. The hammer is supplied with impact tips of varying hardness. It was observed in the testing that for the higher frequencies of test, the harder tips were required to ensure a reproducible tip displacement vibration.

To eliminate the problem of multiple hits with the impact hammer and to ensure a constant impact location, an electromagnetic hammer was developed and used at the University of Delaware. The hammer consisted of a pull-type solenoid, a linkage and the force transducer from the modally tuned impact hammer. Some external circuitry was also developed to control the length of time the solenoid is energized and the voltage that is supplied to the coil. The pivot point of the linkage is located on the lower portion of the clamping fixture and the tip of the force transducer strikes the sample from the bottom as shown in figure 3.

Prior to testing, the operator adjusts the timing circuit and voltage supply until the desired impulse is achieved. In general, the highest voltage that does not induce significant aerodynamic

damping is desired. The ability to vary the coil voltage and therefore the magnitude of the tip deflection enables aerodynamic damping to be minimized

EDDY CURRENT PROBE

To minimize any adverse effects of the added mass of an accelerometer to the beam tip, a non-contact eddy current probe was used to monitor beam tip displacements. This probe was a Kaman Instrumentation Model KD2310-3U which can detect and monitor both magnetic and nonmagnetic materials. The probe was attached to a plexiglas holder which was attached to an x-z vernier. The vernier is bolted to a breadboard baseplate to provide stability and ease of positioning with respect to the specimen. At the University of Delaware, the eddy current probe was attached to a plexiglas holder which was manually positioned and free standing on the base plate.

The signals from the transducer are first calibrated with a similar specimen using a micrometer calibration fixture. The eddy current probe was calibrated so that at a displacement of ± 40 thousandths of an inch, the output recorded by the A-D data acquisition board was ± 1 volt. The output of the eddy current probe was then determined at various positions between +0.04 and -0.04 in. A linear fit was then determined for the data and used in the conversion of the voltage output to displacement in the data acquisition computer program. This results in a displacement resolution of approximately 0.0001 in. The data and the linear

fit are given in figure 4.

DATA REDUCTION

At DTRC, the output signals from the instrumented force hammer and the eddy current probe were input to an IBM PC-AT. This analogue signal was converted using the MetraByte DAS16 A-D data acquisition board and stored in a file. This data was then manipulated using Interactive Laboratory Software by Signal Technologies, Inc. An FFT of the displacement vs. time information is then performed. The FFT in the vicinity of the resonant frequency is then extracted from the file and stored as the left and right side of the peak value. This is readily recognized by the 2π phase shift in the FFT as determined using the ILS software.

A fourth order orthogonal curve fit is then made of the right and left side values of the FFT. The coefficients are recorded and used as input into a computer routine which determines the intersection of the two curves and the values on each of the curves which are .707 of the value at this intersection, known as the half power points. The loss factor is then determined using the half power band width method as

$$\eta_n = \frac{\Delta f}{f_n} = \frac{(f_2 - f_1)}{f_n} \tag{3}$$

where Δf is the bandwidth at the half-power points, f_2 and f_1 are the frequencies of the half-power points and f_n is the

resonant frequency for the n^{th} mode. It should be noted that, in general, an excellent agreement was obtained between the experimentally determined resonant frequency and that determined using equation 2. The coefficient of variation between the experimentally determined values of the resonant frequencies were less than 5%.

A more detailed description of the experimental procedure is given in reference 5. In addition, reference 5 details the calibration of the test fixturing used in this investigation. The results from this testing were that other sources of energy dissipation are minimized by the apparatus used in the investigation.

At the University of Delaware, the data reduction was performed using a GenRad 2500 series FFT Analyzer equipped with Interactive Signal Analysis software. An FFT of both the input and response functions are first determined. The transfer function, T(f), is then obtained where

$$T(f) = \frac{D(f)}{I(f)} \qquad (4)$$

and D(f) is the Fourier transform of the tip displacement vs. time response and I(f) is the Fourier transform of the impulse excitation vs. time response. The frequencies at which the peak values of the transfer function occur correspond to the resonant frequencies of vibration of the specimen.

The values of the transfer function at the peak are then determined using the point by point interrogation feature of the

FFT analyzer. Linear interpolation between digitized points was used to determine the half power points. It was determined that approximately 20 points within Δf were necessary for accurate, reproducible damping measurements.

Both experimental procedures were calibrated using a well characterized material, 2024 T-4 aluminum at DTRC and 6061 T-6 aluminum at the University of Delaware. The experimentally determined loss factors were compared with the analytically determined loss factor obtained from Zener Thermoelastic Theory.(8) The experimental results showed excellent agreement with the analytical values. Details of the testing and results are given in references 5 and 9.

RESULTS AND DISCUSSION

In this section the experimental results for the unidirectional continuous fiber laminates are summarized to provide insight into the influence of fiber and matrix material as a function of frequency on the damping loss factor of composites. In addition, the effect of thickness on the damping loss factor can be assessed.

The results are summarized in tabulated form in Tables A1-A6. Results for the glass/epoxy 20 ply samples for the 0 and 90 degree samples are presented in Tables A1 and A2, respectively. The graphite/epoxy results for the 0 and 90 degree 20 ply samples are presented in Tables A3 and A4, respectively. The AS4/3501-6 0 and 90 degree 8 ply and 32 ply results are given in Table A5.

The graphite/PEEK results are given in Table A6.

GENERAL TRENDS: INFLUENCE OF THICKNESS

The influence of specimen thickness on damping loss factor was investigated for the graphite/epoxy material by testing 8, 20 and 32 ply laminates with 0 and 90 degree orientations. The 8 and 20 ply samples showed no difference in loss factor. The 32 ply laminate had a loss factor that was approximately 50% less than the 8 and 20 ply samples in the 0 degree orientation and approximately 26% less in the 90 degree direction. From this testing, it is seen that the loss factor had only a minimal dependence on specimen thickness. If cyclic heat flow, as described by the Zener Thermoelastic Theory, is an important energy dissipation mechanism for composites (in metals this accounts for all of the energy dissipation (10)), then damping should be extremely sensitive to thickness.

From Zener Thermoelastic Theory, the loss factor is determined as

$$\eta = \frac{\alpha^2 \; ET}{c} \; \frac{\omega\tau}{(1+\omega^2\tau^2 \;)} \tag{5}$$

where E is the Young's modulus, T is the absolute temperature at which the test is conducted, ω is the frequency, c is the specific heat, α is the coefficient of thermal expansion, and τ is the relaxation time. The relaxation time is defined as the time to reach a uniform transverse temperature distribution:

$$\tau = \frac{h^2 \; c}{\pi^2 \; k} \tag{6}$$

where h is the beam thickness and k is the thermal conductivity.

The results of the testing, showing minimal variation of loss factor with thickness, can be explained by examining the relaxation time for the graphite/epoxy composite. The magnitude of the relaxation time for the 8 and 32 ply specimens is approximately 0.1 and 1.5 seconds, respectively. The first resonant frequency for these specimens were approximately 21 and 52 Hz. In both cases, time required for one cycle of vibrational motion is less than this relaxation time. As such, there is no time for the heat to be dissipated through the thickness of the specimen. In addition, as the resonant frequency is increased, the relaxation time becomes greater than the time required to collect the data for analysis. As such, any energy dissipation through heat transfer appears to be minimal at best.

GENERAL TRENDS: INFLUENCE OF FIBER PROPERTIES

The influence of fiber properties can be assessed for both the 0 and 90 degree epoxy matrix composite materials. The fiber characteristics of the graphite and glass are significantly different. The glass is an isotropic fiber whereas the graphite is highly anisotropic. Carbon fibers are composed of long ribbons of turbostratic graphite oriented more or less in the fiber direction.(11) These ribbons are grouped together in stacks about 20 Å thick.(11) The normals to the basai plane of the stacks are randomly oriented perpendicular to the fiber axis, i.e. diffraction patterns of carbon fibers have fiber texture.

consequently, carbon fibers have high stiffness and strength only in the fiber direction, in which carbon-carbon covalent bonds can bear the load. The turbostratic graphite ribbons are held together by van der Waals bonds, resulting in low strength and stiffness transverse to the fiber axis.

These differences in material characteristics result in significant differences in material properties. For the 0 degree configuration, the graphite/epoxy has a modulus approximately 3 times greater than the glass/epoxy. All mechanical properties in the 0 degree orientation are fiber dominated. For an equivalent input excitation force, the load experienced by the matrix will be significantly different in the two composite systems. In the 90 degree orientation, the glass/epoxy has a modulus which is approximately 60% greater than the graphite/epoxy. In this configuration, the graphite fiber can be more readily deformed and may contribute to the damping of the composite. For the glass/epoxy, any additional energy dissipation experienced in the 90 degree orientation compared to the 0 degree orientation would be attributed to the damping of the matrix material.

The 90 degree glass/epoxy has a higher loss factor than the graphite at frequencies greater than 120 Hz. At low frequencies, the graphite epoxy had a loss factor up to a factor of 2 greater than the glass/epoxy. For the 0 degree orientation, the glass/epoxy has a loss factor which is greater than the graphite/epoxy over the entire frequency range. The results are

readily seen in graphical form in figures 5 and 6 for the 90 and 0 degree orientations respectively.

These results are somewhat surprising. It was thought that the glass/epoxy would have a higher loss factor than the graphite/epoxy over the entire frequency range. This assumption, however, is based on the results of other investigators where they reported damping loss factor data of these types of systems without reference to frequency.(12-16) In general, however, their results indicated that the glass composites had a loss actor that was consistently greater than the graphite/epoxy.

GENERAL TRENDS: INFLUENCE OF MATRIX PROPERTIES

The influence of matrix properties can be deduced by comparing the graphite/epoxy and the graphite/PEEK damping results. Both of these materials use the identical AS4 fiber and have similar fiber volume fractions. For the 0 degree orientation, the damping is essentially equal (see Tables). This result is not surprising since material characteristics are fiber dominated in this orientation. In the 90 degree configuration, the graphite/PEEK material had a loss factor which is approximately 50% less than the graphite/epoxy (see Tables).

It should be noted that it was initially thought that the APC-2 would have a higher loss factor than the graphite/epoxy because of the differences in material characteristics of the resin. The epoxy is a homogeneous isotropic material system. The PEEK is a two phase semicrystalline material. As such, it was

thought that the two-phase nature may cause an increase in damping, for example through additional shear or stress variation at the interface between the amorphous and crystalline phases. This, however, was not the case in this testing program. It appears that crystallinity is not a significant contributor to material damping. More testing over a wider frequency range is required.

GENERAL TRENDS: INFLUENCE OF FREQUENCY

The frequency range tested in this program was up to 1000 Hz. Loss factors were determined at approximately every 20 Hz. at frequencies below 100 Hz. and every 100 Hz. from 100 - 1000 Hz. The experimentally determined loss factors versus frequency are shown for the 0 degree orientation in figure 5 and the 90 degree orientation in figure 6.

For the 0 degree configuration, the loss factor of the graphite/epoxy material increased linearly with frequency as shown in figure 5. The loss factor of the glass/epoxy decreased initially from approximately 40 to 380 Hz. then increased up to the terminal frequency of approximately 960 Hz. The graphite epoxy data was similar to the type of information which can be compiled from other investigators. Although no single investigation determined the loss factor over a range of frequencies, assembling the loss factor as a function of frequency from various investigations shows that the loss factor increases as a function of frequency.(12,17,18) The same trend is

obtained for the glass/epoxy through the compilation of data from other investigators. The reason that the information developed herein showed an initial decrease in loss factor as a function of frequency may be due to the specific beam test configuration utilized.

The glass/epoxy composite has a stiffness which is approximately 8 Msi. For the low frequencies, long beam lengths are used (see Tables). Because of the long beam length and low stiffness, the cantilevered beam takes on a slight curvature as it is held in its fixture. This, along with gravitational effects, may result in loss factor values which are higher than anticipated. As the beam length is decreased, the curvature is reduced which may result in a more characteristic material loss factor.

For the 90 degree orientation, the loss factor varied in a more complex manner with frequency (see figure 6). The loss factor of the glass/epoxy increased up to the maximum test frequency, although the increase appeared to plateau between 200 and 600 Hz. Since the characteristics of this configuration is matrix dominated, it is anticipated that the loss factor would be similar to that of the bulk resin material. Although the loss factor for this bulk resin was not determined, general viscoelastic materials typically show an increase in loss factor with increasing frequency over the frequency range tested.(6)

For the 90 degree graphite/epoxy, the maximum loss factor occurred at the lowest test frequency, decreasing monotonically to the highest test frequency of 440 Hz. This result was not anticipated. Again, it was assumed that the loss factor would increase with frequency since the material characteristics of this test configuration is matrix dominated. The reason for the results obtained may be due to the low stiffness and long beam lengths for the low frequency, as was discussed previously for the glass composite 0 degree configuration.

CONCLUSIONS

Material damping of continuous fiber organic matrix composites was experimentally determined using a cantilever beam test specimen geometry and an impulse excitation technique. The damping loss factor for 0 and 90 degree glass/epoxy (Hercules S2 Glass/3501-6), graphite/epoxy (Hercules AS4/3501-6) and graphite/polyetheretherketone (ICI APC-2) are measured. Damping is found to be effected by fiber type, matrix type and fiber orientation. In general, the damping increases with increasing frequency for both orientations with the exception of the 90 degree graphite/epoxy. Here, the loss factor decreased with increasing frequency. The variation of loss factor with frequency appears quite complex, whereas the loss factor for the 0 degree graphite/epoxy orientation increases linearly with frequency. Damping was found to be relatively insensitive to specimen thickness.

The results from the 0 degree glass/epoxy and 90 degree graphite/epoxy were markedly different than anticipated. This may be the result of the cantilever beam position used. When low stiffness beams are oriented in a horizontal position, beam curvature and gravitational effects may alter loss factor values. Another investigation is currently underway where the specimen will be positioned in a vertical cantilever beam orientation, thereby minimizing both the gravitational and curvature effects.

ACKNOWLEDGEMENTS

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Figure 1: Schematic of experimental apparatus designed at DTRC for testing the vibration damping loss factor of composites

Figure 1a: Schematic of experimental equipment

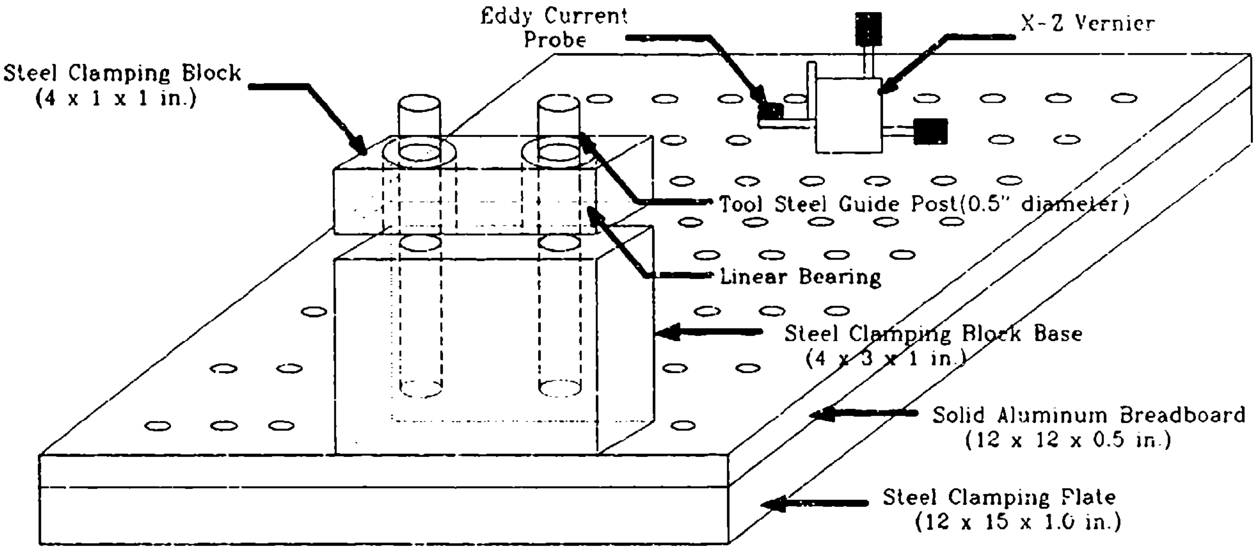
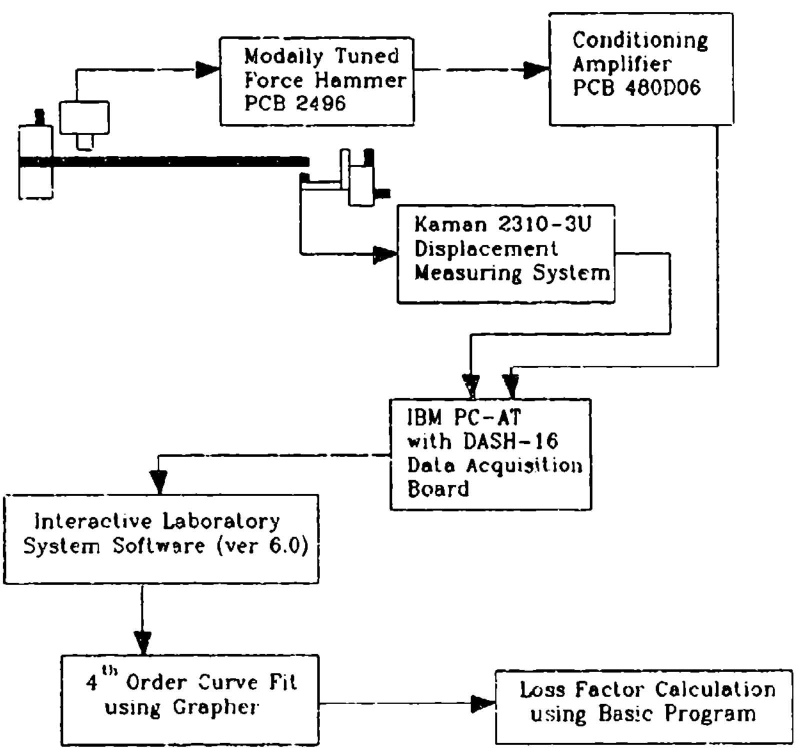


Figure 1b: Schematic of data acquisition system



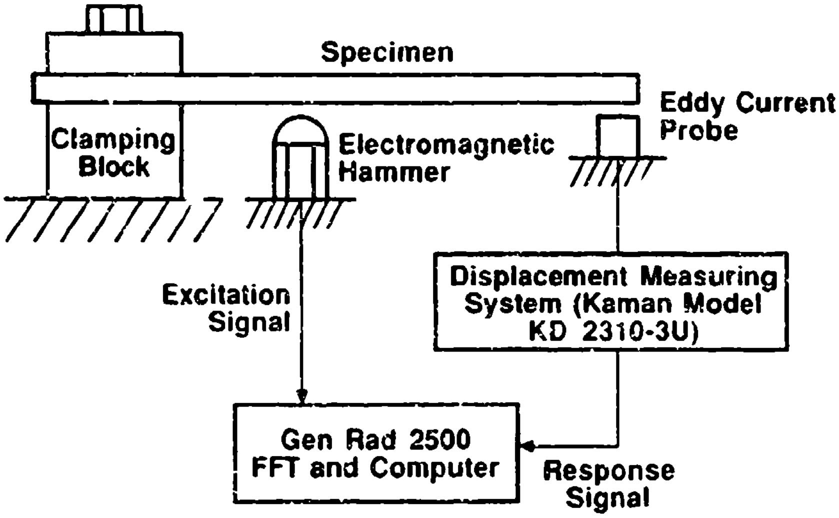


Fig. 2 Schematic of experimental apparatus designed at the University of Delaware for testing the vibration damping loss factor of composites

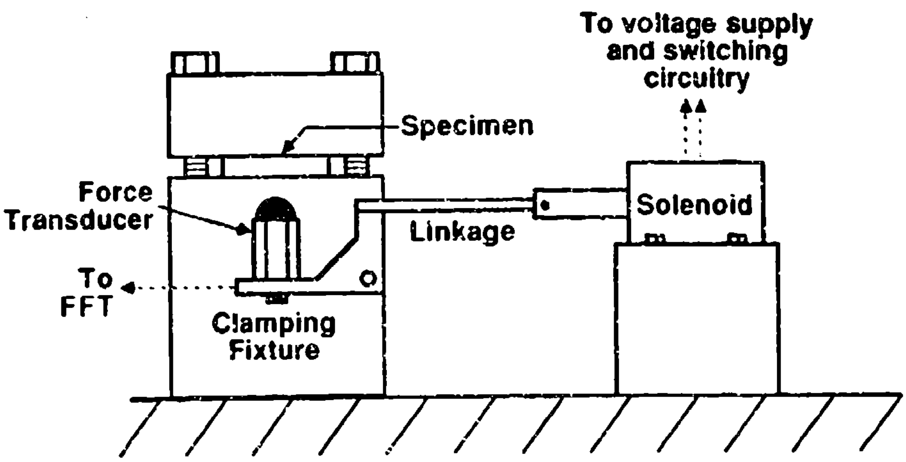
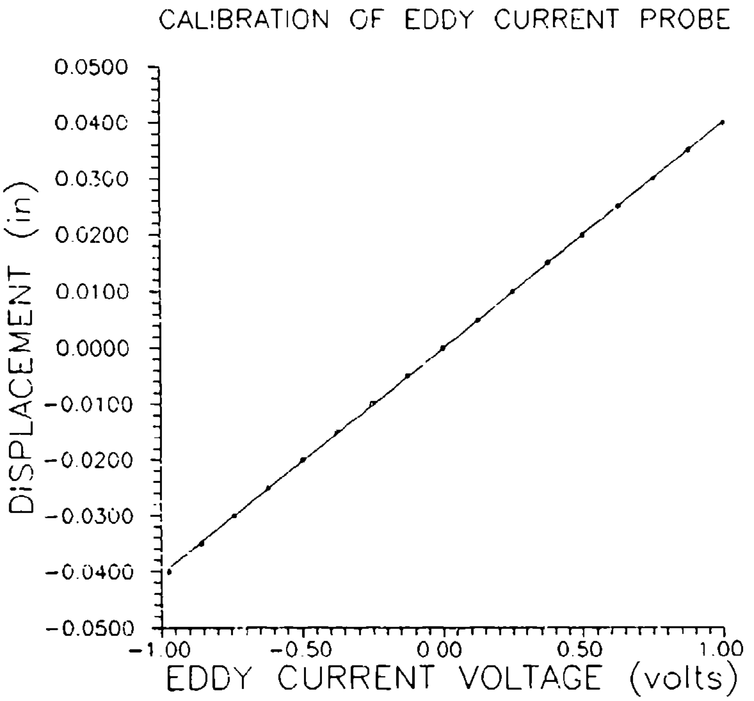
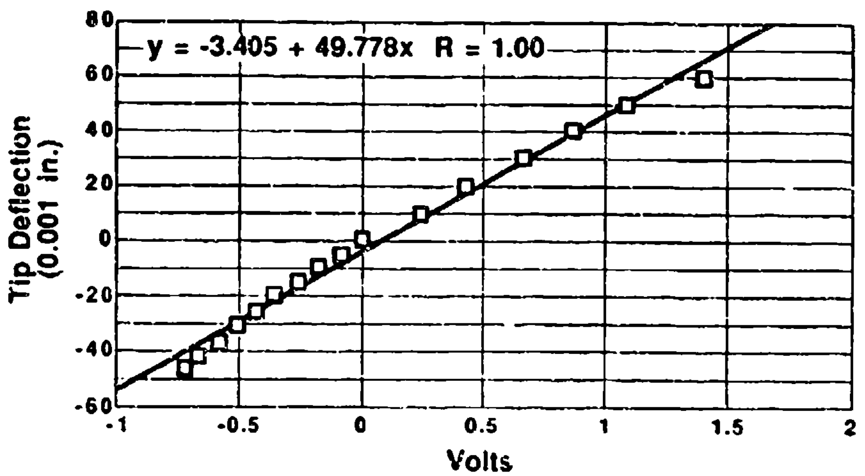


Fig. 3 Schematic of electromagnetic hammer apparatus

Fig. 4 Calibration of eddy current voltage vs. displacement



a. DTRC



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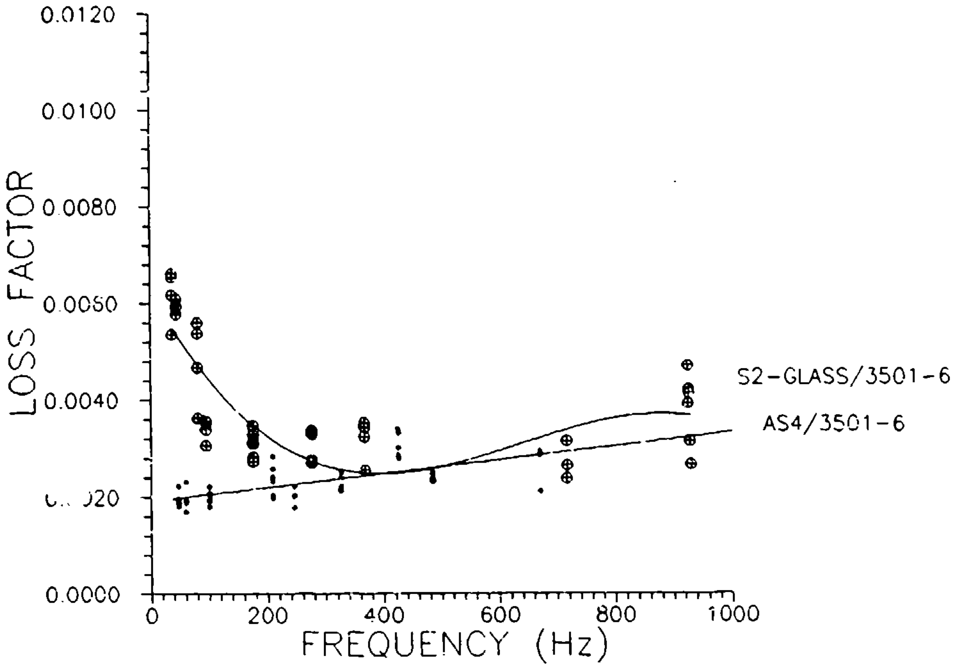

Fig. 5 Experimentally determined vibration damping loss factor vs. frequency for 0 degree glass/epoxy (Hercules S2-Glass/3501-6) and graphite/epoxy (Hercules AS4/3501-6)

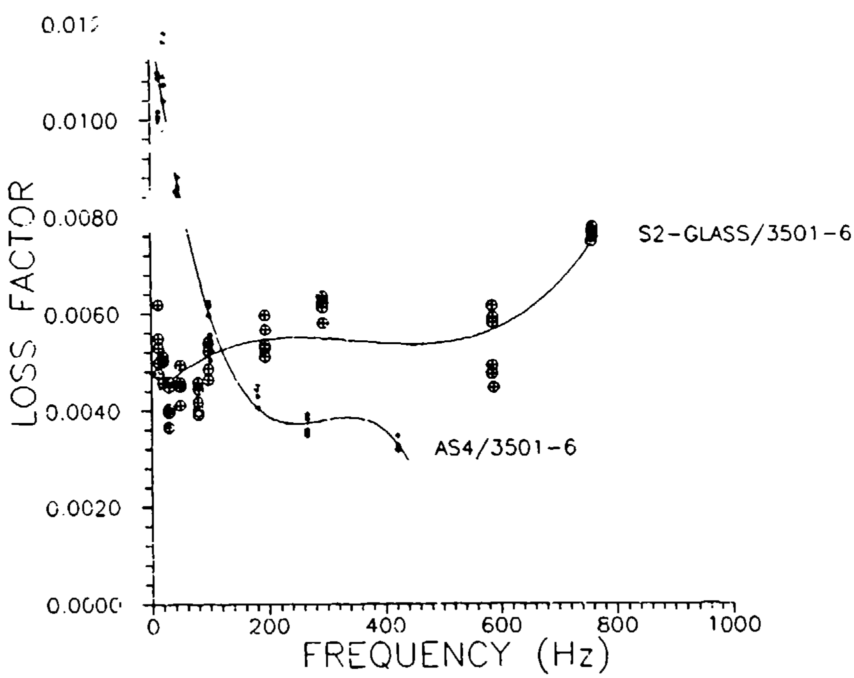

Fig. 6 Experimentally determined vibration damping loss factor vs. frequency for 90 degree glass/epoxy (Hercules S2-Glass/3501-6) and graphite/epoxy (Hercules AS4/3501-6)

Table A-1: S2 Glass/3501-6 $[0]_{20}$ glass/epoxy damping data

BEAM LENGTH (in.)	RESONANT FREQUENCY (Hz)	LOSS FACTOR ($\times 10^{-4}$)
8.8125	37.818	61.742
8.8125	37.840	53.536
8.8125	37.844	65.335
8.8125	37.866	66.149
8.0	45.601	60.934
8.0	45.627	57.717
8.0	45.648	59.511
8.0	45.660	59.208
6.0	81.117	55.927
6.0	81.119	53.681
6.0	81.154	36.186
6.0	81.497	46.678
6.0	81.555	46.632
5.5	94.735	35.512
5.5	94.833	30.579
5.5	94.851	33.880
5.5	95.325	35.503
5.5	95.327	35.409
5.5	95.423	35.410
4.0	175.546	34.593
4.0	175.655	32.816
4.0	175.752	31.498
4.0	175.796	30.940
4.0	175.916	27.282
4.0	176.163	28.132
3.234375	276.131	26.944
3.234375	276.188	33.591
3.234375	276.267	32.797
3.234375	276.331	27.101
3.234375	276.553	33.416
3.234375	276.595	27.553
2.75	366.756	35.231
2.75	367.354	32.360
2.75	367.479	34.259
2.75	368.740	25.488

Table A-2: S2 Glass/3501-6 $[90]_{20}$ glass/epoxy damping data

BEAM LENGTH (in.)	RESONANT FREQUENCY (Hz)	LOSS FACTOR ($\times 10^{-4}$)
11.84375	12.8283	55.0280
11.84375	12.7949	49.9250
11.84375	12.8765	52.9645
11.84375	12.8163	47.7420
11.84375	12.8459	61.9003
9.515625	19.9660	50.3042
9.515625	19.9252	45.8076
9.515625	19.8984	50.1035
9.515625	19.9300	51.3104
7.765625	29.9902	36.7393
7.765625	30.0246	36.5254
7.765625	29.9463	44.9431
7.765625	30.0112	40.4229
7.765625	30.0171	45.9937
7.765625	30.0349	39.7218
6.03125	49.2336	45.8412
6.03125	49.2016	41.1675
6.03125	49.2024	45.1763
6.03125	49.2385	49.4467
6.03125	49.1861	44.9494
5.71875	79.7479	45.9238
5.71875	79.7944	44.4997
5.71875	79.7868	39.2332
5.71875	79.7312	41.8561
5.71875	79.7642	40.0591
4.25	97.9258	46.4685
4.25	98.0275	48.6442
4.25	97.8354	52.3654
4.25	98.0011	54.0049
4.25	97.9806	54.1517
2.984375	195.0699	51.1757
2.984375	194.7481	52.8341
2.984375	194.8285	59.7262
2.984375	194.5963	53.6054
2.984375	195.7036	56.6583
2.453125	293.9756	62.3772
2.453125	294.1466	61.2320
2.453125	294.6329	62.2536
2.453125	294.1912	63.5808
2.453125	294.6956	58.0343

Table A-2: S2 Glass/3501-6 $[90]_{20}$ glass/epoxy damping data (cont)

BEAM LENGTH (in.)	RESONANT FREQUENCY (Hz)	LOSS FACTOR ($\times 10^{-4}$)
1.734375	585.6718	47.5699
1.734375	587.9997	44.7396
1.734375	586.4592	49.2601
1.734375	586.0698	61.5899
1.734375	586.8231	58.0462
1.734375	587.3039	59.1875
1.5	758.7123	74.7027
1.5	759.1497	76.9423
1.5	760.4854	75.8990
1.5	760.6876	77.6526
1.5	760.7842	78.3620

Table A-3: AS4/3501-6 $[0]_{20}$ graphite/epoxy damping data

Beam Length (in.)	Frequency (Hz)	Loss Factor (x 10^{-4})
4.0	325.71	21.309
4.0	326.04	21.246
4.0	326.32	23.848
4.0	326.54	24.942
4.0	326.63	22.217
4.5	246.42	20.258
4.5	246.20	22.164
4.5	246.51	17.846
4.5	246.53	20.121
5.0	209.19	23.192
5.0	209.29	25.720
5.0	209.38	28.282
5.0	209.41	24.070
5.0	209.47	20.255
5.0	209.64	19.726
7.25	100.27	20.780
7.25	100.32	19.209
7.25	100.35	22.140
7.25	100.62	18.021
7.25	100.66	19.864
9.375	60.42	23.053
9.375	60.43	19.605
9.375	60.53	19.173
9.375	60.54	16.955
9.375	60.62	18.779
10.34375	48.54	18.156
10.34375	48.54	19.645
10.34375	48.55	22.276
10.34375	48.58	18.868
10.34375	48.59	19.315
10.34375	48.59	19.130

Table A-4: AS4/3501-6 $[90]_{20}$ graphite/epoxy damping data

BEAM LENGTH (in.)	RESONANT FREQUENCY (Hz)	LOSS FACTOR ($\times 10^{-4}$)
10.34375	14.90	109.774
10.34375	14.93	99.835
10.34375	14.93	100.711
10.34375	14.94	101.748
10.34375	14.95	108.674
8.0	25.00	97.630
8.0	25.00	109.152
8.0	25.01	104.044
8.0	25.03	116.272
8.0	25.05	107.351
8.0	25.06	117.887
6.0	44.20	85.394
6.0	44.77	92.542
6.0	44.85	93.533
6.0	44.87	94.634
6.0	47.10	84.442
6.0	47.11	86.121
6.0	47.12	88.135
6.0	47.16	82.131
4.0	100.02	62.552
4.0	100.07	61.651
4.0	100.09	59.631
4.0	100.22	59.760
3.75	101.40	61.775
3.75	101.44	50.502
3.75	101.51	55.716
3.75	101.59	52.221
3.75	102.40	54.091
3.0	179.96	44.476
3.0	181.50	45.259
3.0	181.96	42.995
3.0	182.27	40.654
2.375	266.64	38.301
2.375	266.74	34.811
2.375	266.87	39.288
2.375	266.90	35.157
2.375	266.92	36.070
1.875	422.35	34.659
1.875	422.54	31.644
1.875	422.75	32.743
1.875	423.15	32.189

Table A-5: AS4/3501-6 [0] Graphite/Epoxy Loss Factor Data

SPECIMEN BEAM LENGTH (cm)	BEAM THICKNESS (mm)	FIRST RESONANT FREQUENCY (Hz)	DAMPING LOSS FACTOR
25.4	1.02	21.14	20.7851E-4
33.0	4.06	52.44	10.8613E-4

AS4/3501-6 [90] Graphite/Epoxy Loss Factor Data

SPECIMEN BEAM LENGTH (cm)	BEAM THICKNESS (mm)	FIRST RESONANT FREQUENCY (Hz)	DAMPING LOSS FACTOR
25.4	1.02	6.08	94.2385E-4
33.0	4.06	14.85	69.1390E-4

Table A-6: AS4/PEEK (APC-2) $[0]_8$ Graphite/PEEK Loss Factor Data

SPECIMEN BEAM LENGTH (in)	FIRST RESONANT FREQUENCY (Hz)	DAMPING LOSS FACTOR
10.0	20.62	16.8866E-4

AS4/PEEK (APC-2) $[90]_8$ Graphite/PEEK Loss Factor Data

SPECIMEN BEAM LENGTH (in)	FIRST RESONANT FREQUENCY (Hz)	DAMPING LOSS FACTOR
10.0	6.43	48.6845E-4

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